33 Fiber-Optic Network Components

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INTRODUCTION

The popularity of fiber-optic systems for communication and networking, including in process industry, has resulted in great developments and implementations in the last decade. The implementations of fiber-optic systems are growing at an unprecedented pace in industrial applications. The art of optical design has multi-dimensional considerations. There is a need for good design strategy for the current specific needs as well as possible future expansion and augmentation of the systems. The literature is enriched with many different approaches for designing fiber-based optical systems. In general there is a valuable number of R&D on issues of network architecture, network simulations, fault tolerance, and challenging issues for fiber-optic–based systems. In addition, there also is a necessary knowledge based about the hardware capabilities and possibilities that can enable designers envision better and richer systems. The purpose of this chapter is to provide an overall overview of hardware, devices, and subsystems. The authors' goal is to provide a useful and practical basis for understanding the major entities in the design, as well as providing good reference for those who are interested in going more in-depth in this area. It is not possible to cover all of the devices, systems, and subsystems. Consequently, the goal of this chapter is to provide a useful overview of what is needed to be considered when studying, designing, or just understanding an optical, optoelectronic, or related optical fiber–based system.

OPTICAL NETWORKS

History of Optical Communication

One of the earliest documented optical networks is the Roman smoke signal telegraph, which dates back to 150 A.D. To keep pace with the rapid pace of the expansion of their empire the Romans developed a highly sophisticated network of towers within visible range of each other. This first optical network spanned a total distance of 4500 km and used smoke signals to relay military messages.

Another famous optical network is the Chappe optical telegraph network of the eighteenth century. The French revolution, epoch of the rise of capitalism, required France to defend itself from enemies both within and without. This situation highlighted the importance of high-speed, long-distance communications and Claude Chappe, a former priest, designed and built the first optical telegraph. Spanning a distance of 200 km, it linked Lille and Paris via a series of 15 towers space 12–25 km apart. Each tower was equipped with telescopes and mechanical semaphore arms, which could be reconfigured to display 196 distinct characters. These were manually relayed by operators from tower to tower and peak message speeds of 3000 km/h were achieved. This network was highly successful and continued to expand until 1846, spanning 5000 km with 556 stations. Many concepts in modern networks, for example, flow control, error detection and synchronization had their inception in the Chappe telegraph [21].

Samuel Morse ushered in the era of electrical communications in 1837 with the invention of the telegraph [38]. For the ensuing century, optical communications remained largely supplanted. Its comeback had roots in the 1870 demonstration of transmission of light by total internal reflection in a stream of water by John Tyndall, which marked the inauguration of research into the guided transmission of light. About a decade later, Alexander Graham Bell developed a voice transmission system, dubbed the photophone [5], which employed free-space optics and had a range of 200 m. Limited by line-of-sight requirements, it was not until the invention of both a powerful coherent optical source that could be modulated lasers [34] and a flexible, sufficiently low-loss transmission medium optical fibers [26,27] that the tide was turned.

Modern Optical Communications

Contemporary optical fibers are a far cry from their original counterparts (Figure 33.1). Due to their characteristics, modern optical communications utilize the medium (1310 nm) and long (1550 nm) wavelength bands or transmission windows due to the least dispersion and attenuation in those windows, respectively. The availability of sources and amplifiers at these wavelength windows is also an integral factor for communications purposes. The latest zero water peak (ZWP) fibers manufactured using vapor-phase axial deposition removes the attenuation peak at 1383 nm due to optical absorption and scattering by water ions. This opens up a very

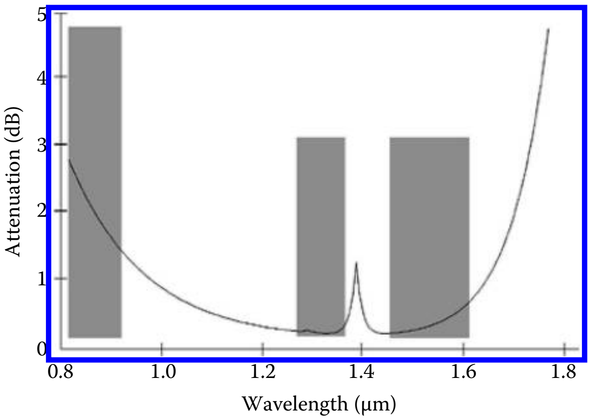

FIG. 33.1
Optical transmission windows. The curve is for modern fiber with a water attenuation peak at 1383 nm.

broad wavelength window spanning 1285–1625 nm with an attenuation constant of ≤0.33 dB/km at 1310 nm, ≤0.31 dB/km at 1383 nm, and ≤0.19 dB/km at 1550 nm (PureBand® ZWP Fiber Specification 2008).

Commensurate with the wavelength windows identified above, optical fibers have a large potential transmission capacity. The amount of information that can be transmitted is directly related to the frequency range over which the carrier operates. An increase in the carrier frequency theoretically increases the transmission bandwidth. Referring to Figure 33.1, it is seen that both the medium and long wavelength bands exhibit very low loss, around 0.4 dB/km for the second window (medium wavelength, 1250–1350 nm) and 0.2 dB/km for the third window (long wavelength, 1450–1600 nm). The useful wavelength range is therefore about 250 nm.

Expressed in terms of analog bandwidth, a 1 nm waveband translates to a bandwidth of 178 GHz at 1300 nm and 133 GHz at 1500 nm. Thus, optical fibers have a total usable bandwidth of approximately 30 THz. The information carrying capacity depends on the modulation technique used. Assuming the widely used on–off keying format is used, which has a maximum theoretical bandwidth efficiency of 1 bps/Hz, one can expect a digital bandwidth of 30 Tbit/s if fiber non-idealities are ignored. The removal of the water absorption peaks by ZWP fibers serves to further increase this already phenomenal figure.

Given the large of optical fibers, it comes as no surprise that they are predominantly replacing copper as the transmission medium of choice, vastly increasing single-link bandwidth in the process. As shown in Figure 33.2, the past decade has witnessed a networking paradigm shift from connection-oriented communication to high bandwidth IP-centric packet switched data traffic, driven by the influx of high bandwidth applications [8]. Home entertainment applications such as high-definition television are pushing the capabilities of current cable network technologies, video-conferencing applications are challenging current commercial network technologies and the growing complexity of commercial and military aircraft, including multifaceted sensor arrays and high-definition flight displays, are pushing avionics networks to their limit.

The availability of such applications relies heavily upon the ability to transport data in a fast and reliable manner without significantly increasing operating and ownership costs. As these applications are pushing current network technologies to their capacity limits, researchers are being forced to create high-speed networks capable of supporting the varied bit-rates, protocols, and formats required by these applications in a highly scalable manner.

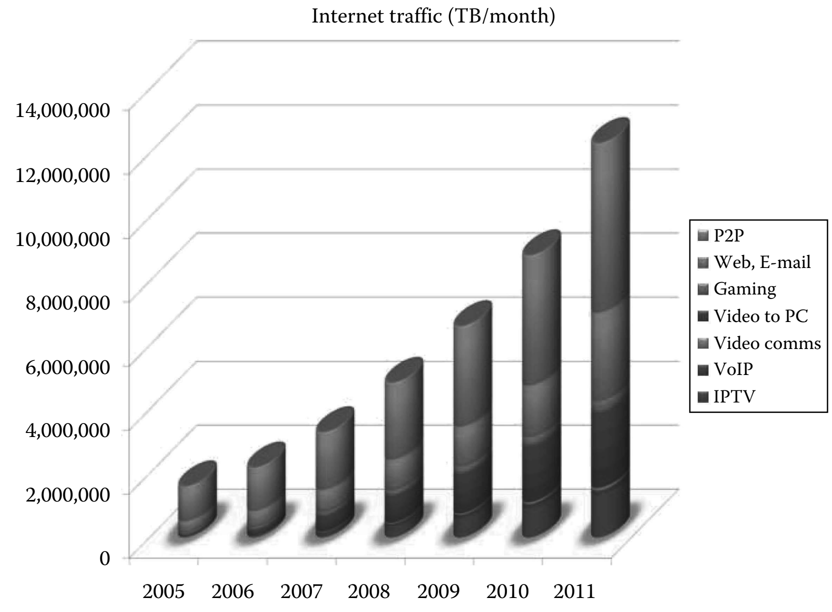

FIG. 33.2
Forecasted growth of global IP traffic.

NETWORKS

To begin understanding optical networks, a logical place to begin is the definition of a network. A communications network is essentially an arrangement or collection of physical links and other equipment in which messages may be passed from one part of a network to another using either a single or multiple links, thereby providing a means of information exchange between end users. A better definition might be that a network is a collection of distributed, intelligent instruments that share data and information through interconnected lines. Breaking down this definition, one could say that a network consists of a collection of distributed (generally not visible to the users), intelligent (robust, stable, high-tech connections that have imbedded possibilities of optional scenarios for different situations that can occur in the interconnection) instruments (computers, switches, routers, repeaters, receivers, monitors, etc.) that share data and information through interconnected lines (copper wires, optical fibers, wireless channels, etc.).

Depending on one's intention and interests, the definition can be presented in arbitrary depth for clearer understanding. It should be noted that, a typical network, as shown in Figure 33.3, will have nodes or instruments and links or connecting lines that are the paths for the signals and data to be shared between the nodes and eventually the users.

Networks can be broadly classified into either communications or data networks, which indicate the type of information that can be sent over the connections. Some of the early data networks that are still being used for research purposes include ARPANET, NSFNET, as well as the Internet, which is a collection of networks and machines that make a worldwide internetworking.

When discussing optical networks, we are referring to a collection of devices in the physical layers (lasers, receivers, fibers, repeaters, couplers, etc.) as well as other rules for management, which is basically an agreement and rules of communicating within the network. Generally speaking, it is accepted that when users refer to optical layers they are focusing on the specific physical layer characteristics that allow transfer of data between users via optical capabilities and instrumentation.

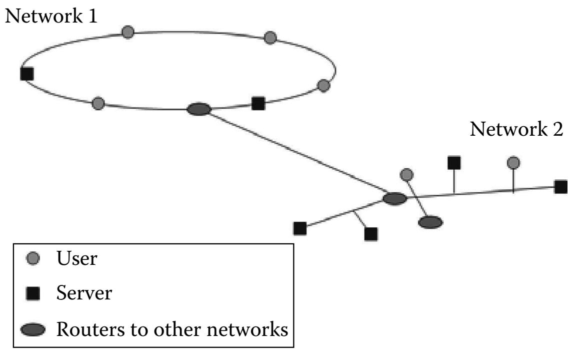

FIG. 33.3
Networks as a collection of nodes and links.

Network Types

For historical reasons, the networking industry refers to network designs as some form of area network and they are generally classified by their scope, scale, and average distance between their constituent nodes (where the computers, servers, switches, routers, etc. are located). Those with a typical distance of 0–100 m are known as local area networks. The networks in which the nodes range from 100 m to a few kilometers apart are known as metropolitan area networks, and wide area networks are those in which the separation between nodes spans 10–100 s of kilometers. Communications networks in which the nodes are greater than 100 s of kilometers apart are known as long-haul networks. An example of this is the underwater fiber-optic cable system between the United States and Japan. This system was the major focus of the telecommunications industry in the 1980s and long-haul optical communications was the dominant driving force for the rapid development of fiber optics and optical components in the mid-to-late 1980s and early 1990s.

Protocols and Services

"Protocol is commonly described as a set of international courtesy rules. These well-established and time-honored rules have made it easier for nations and people to live and work together. Part of protocol has always been the acknowledgment of the hierarchical standing of all present. Protocol rules are based on the principles of civility [19]." The rules and process of the connection and transfer of information are identified with a series of functions. Generally speaking, the functions are organized as series of levels (layers), and each one provides specific services. Each layer is identified by a name, which indicates the type of functional for that particular layer. Figure 33.4 depicts the standard layering scheme known as open system interconnect protocol, which is regarded as the standard model. Perhaps the most recognized data network protocol is TCP/IP, which is fairly well known to most computer users.

The physical layer is concerned with transmitting the data over a communications channel. This layer is the place that the wires, switches, fiber optics, sources, detectors, etc., are included, either accepting data as is and transmitting it to users or accepting data from senders. The data link layer is where the data is shaped into a recognizable form to be transmitted via the physical layer. In this layer, the system can also create some error correction procedures to enable it to detect any loss of data or corrupted bits of information. The network layer controls the way the connection is created from the source to the destination. The transport layer accepts the information from the session layer and breaks it into manageable pieces to be sent to the network layer for the appropriate connection. The session layer is utilized so the users with different machines or instruments can communicate between each other. The presentation layer together with the session layer allows the

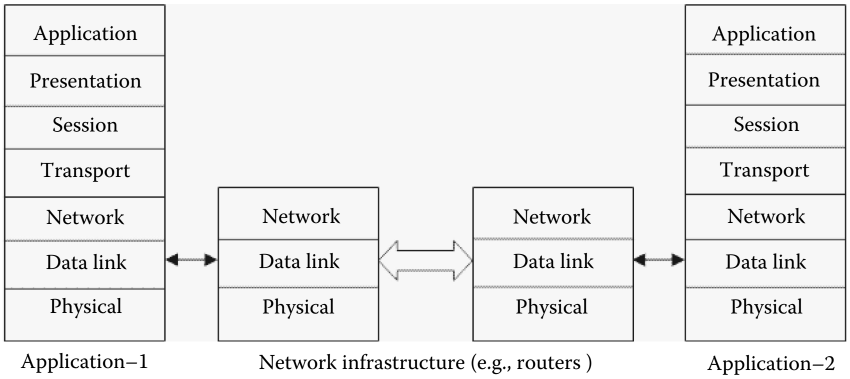

FIG. 33.4
Seven-layer OSI reference model.

data to be presented in a general universal format to be sent and agreed upon over the network. The application layer allows the user and the machine to connect through the appropriate application.

Information Channels and Transport

Before proceeding further, it is important for the reader to review some of the basics of information transport. In general, either the electronics or microwaves or the optical fiber–based networks utilize signals with a given frequency (f measured in Hz) that describes the number of cycles per second, speed (V measured in meters/second), and wavelength (λ in meters), which is the shortest distance the wave travels in space before it repeats itself. Note that the above-mentioned quantities are related with the basic equation $V = f\lambda$.

When light propagates in air or vacuum, it has a speed of around 3×10^8 m/s (or more accurately 2.9979×10^8 m/s). It should be noted that the speed of light changes as it travels in different materials, which usually turns out to be reduced in denser material. The ratio of the speed of light in air or a vacuum to the speed of light in a given material is termed the index of refraction of the material and is identified as n. When an electromagnetic wave of frequency f_1 propagates into a given material, its speed and wavelength change but its frequency remains constant. While the index of refraction of material is represented by an average number, it should be noted that in optical fibers and glass the index of refraction is a function of frequency. Due to the nature of the interaction of a wave with materials, waves of different wavelengths possess different speeds.

Communication and network technologies are usually referred to by their operating frequencies. Figure 33.5 illustrates some of the popular frequency ranges, their applications as well as associated wavelengths. It should be noted that as the frequency of the signal increases, it is easier to refer to the signal in terms of its wavelength. Consequently, it is standard nomenclature to use for instance 1.55 μm instead of 193.55 THz. Commercial optical networks currently utilize the C (1530–1570 nm), S (1450–1530 nm), and L (1570–1620 nm) bands.

Almost all implemented optical networks utilize digital information. It is important for the reader to know how the information transferred in digital networks is quantified. The information is measured in bits per second (bps) and termed the data transmission rate. For instance, a computer modem may be connected at 33,600 bps, which means in each second there are 33,600 bits sent over the line. In digital communications, bandwidth is the number of bits that a given system is capable of handling. This is closely related to analog system bandwidth, which refers to the frequency content of the system in the vicinity of the central operating frequency.

First-Generation Optical Networks

First-generation optical networks fulfilled the need to transmit large amounts of data faster and more economically between a sender and the receiver. They were based on having a connection from the initial to the final point (point-to-point connection). It should be noted that most contemporary network implementations are still based on variations of the first generation of optical networks. In the first generation, the electronic nodes handled all the data. The data had to go through the traditional electronic switches with traditional routing functions. In order to do that, the optical signal had to be translated to an electronic signal, then, after routing and switching, it would be converted back to the optical domain. The typical switches of the first generation received an optical signal from the fiber-optic line. The receiver translated the signal from an optical to an electronic signal. Then the electronic signal was switched electronically; after the switching, the signal was translated to optical form and transmitted on the new fiber. This is an optical–electronic–optical (OEO) switching, and the type of network that is based on such systems is called opaque. It should be noted that the typical electronic systems are much slower compared with the optical systems. Consequently, they are like bottlenecks of information. The motivation for the second-generation

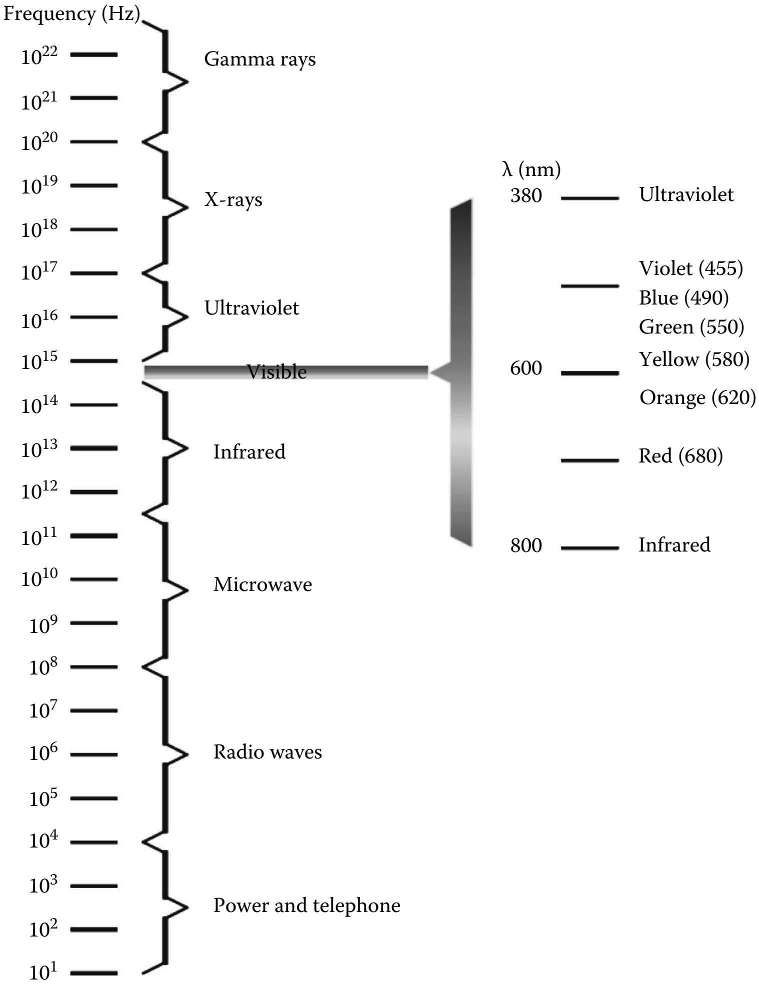

FIG. 33.5
Electromagnetic spectrum.

optical systems is to route and handle optical data streams in an optical domain and try to reduce the burden of the electronic speed and bottlenecks. The light path is not interrupted at any time and the information always stays in an optical domain. Such a system is called a transparent optical system, or an all optical network (AON).

Optical networks can provide a variety of connections and services including:

- *Circuit Switch Networks:* Optical networks can provide paths (optical paths) between points on the network. Once an optical link is established, high-speed data can be sent between the points. In a circuit switch case, once the path is established all of the available bandwidth of the line is available to be used.
- *Packet-Switch Networks:* It is also possible for the system to not have a direct connection between the initial and receiving points. The streams are sent on the line and are routed based on the available resources and line utilization at each point.

Access Schemes

In order to improve the throughput of the communication channels, there are ways that we can send different signals on the same path without interfering with each other. The process of adding many different signals over one path is known as multiplexing. There are more than a few methods of multiplexing the information of the signals. The most popular ones include wavelength division multiplexing (WDM), time division multiplexing (TDM), and code division multiplexing (CDM). This section will briefly describe these methods.

A. *Wavelength Division Multiplexing (WDM):* In long-distance telephone signals that are carried by microwaves (radio waves with high frequency and short wavelengths) there are usually hundreds of voice channels sent over the same microwave path. These signals are transmitted at different frequencies. Each signal is carried over its own channel. Each channel has a center frequency with a band of frequency around it. This scheme is illustrated in Figure 33.6.

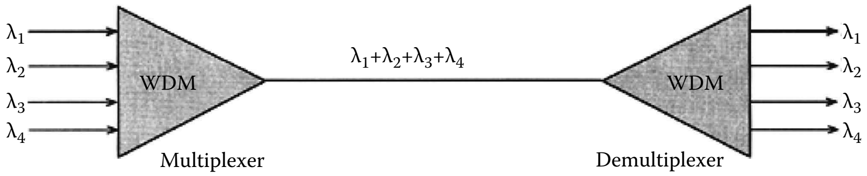

FIG. 33.6
General concept of WDM.

WDM technology was initially developed to increase the capacity of point-to-point fiber links. WDM-enabled networks allow multiple opaque point-to-point connections to be established where the optical signal must undergo OEO conversion at each intermediate node in the network. Network designers are able to occupy multiple wavelengths leading to increased bandwidth and fault tolerance while decreasing congestion and blocking. This method is currently the method of choice for fiber-optic communication and data networks that utilize the high-bandwidth capability of the optical fiber between 1260–1400 and 1520–1600 nm. To date, there are commercially available systems that can make up to 240 channels multiplexed on the same fiber path. While the signal will travel on the same path at the user side, the signal needs to be demultiplexed and filtered and the selected frequency of the information will be processed. The process of having many channels with very narrow bandwidth on the same fiber is referred to dense WDM (DWDM). It is defined by channel spacing less than 1 nm. DWDM is the most promising method of utilizing optical networks. It should be noted that by the new introduction of fibers, where the loss in the 1400–1500 nm is flattened, the number of available channels will dramatically increase.

B. *Time Division Multiplexing (TDM):* While WDM allows many fast channels to coexist together in the same paths (Figure 33.7), time divisions multiplexing allows many slower channels to be added together into a single fast channel. In this method, several different signals are transmitted over the single channel, each transmitted at a different time slot. It should be noted that most of the optical networks are utilizing WDM. However, in order to provide more efficient service, the traffic is groomed between channels and time slots by utilizing TDM. Other access methods like CDM and SDM are utilized in particular systems. CDM is a method that allows each user to utilize the entire frequency band at all times. This concept is also known as spread spectrum. In CDM, multiple transmissions at the same time can be done by utilizing a coding method that allows each user to have a code and identify the signals that are only sent to the particular user; all other signals are ignored or filtered out.

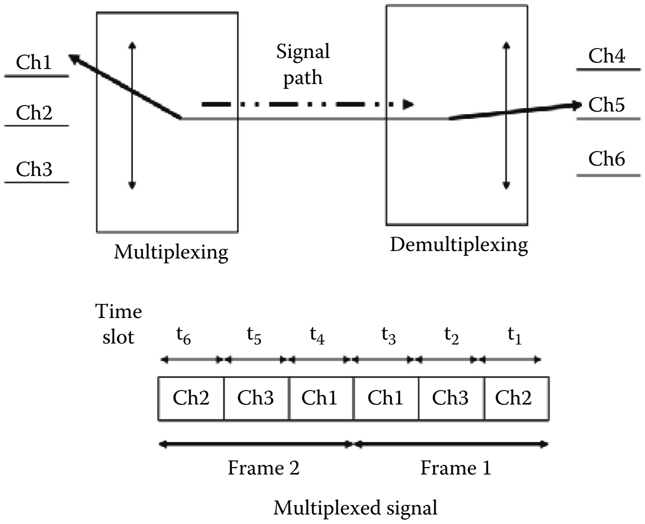

FIG. 33.7
General concept of TDM.

Topologies

When a network is connected, there are two aspects of the interconnection that can be focused on. The first is the physical topology, which is the interconnection from the hardware standpoint. In this view, the network is made of nodes and links. This is when optical lines and nodes physically connect. The other view is the logical topology, which is the way the actual light paths are set to travel and connect. These concepts are illustrated in Figure 33.8. The various possible network topologies are shown in Figure 33.9.

1. *Single-Hop Networks:* In such a network, each node is attached to an optical multiplexer, which connects all of the inputs to the outputs. Every output gets a copy of what every input is sending. In a single-hop WDM network, the data remains in the same frequency until it reaches its destination. As a result, while transmitting, the transmitter of the sending node and the receiver of the destination have to be tuned to the same wavelength. Consequently, for fast and broadband operation between selected nodes, sources and receivers must be capable of rapidly being tuned to different frequencies.
2. *Multi-Hop Networks:* An obvious way to avoid the need for a fast tunable transmitter or receiver is a multi-hop network. In these networks, a node is assigned one

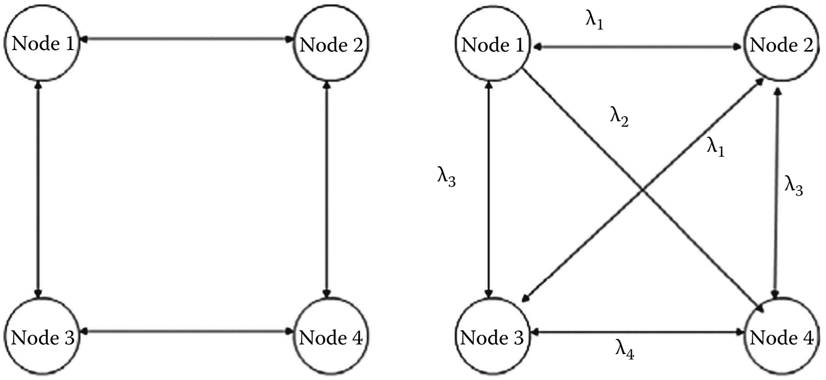

FIG. 33.8
Physical (left) and logical (right) network topologies.

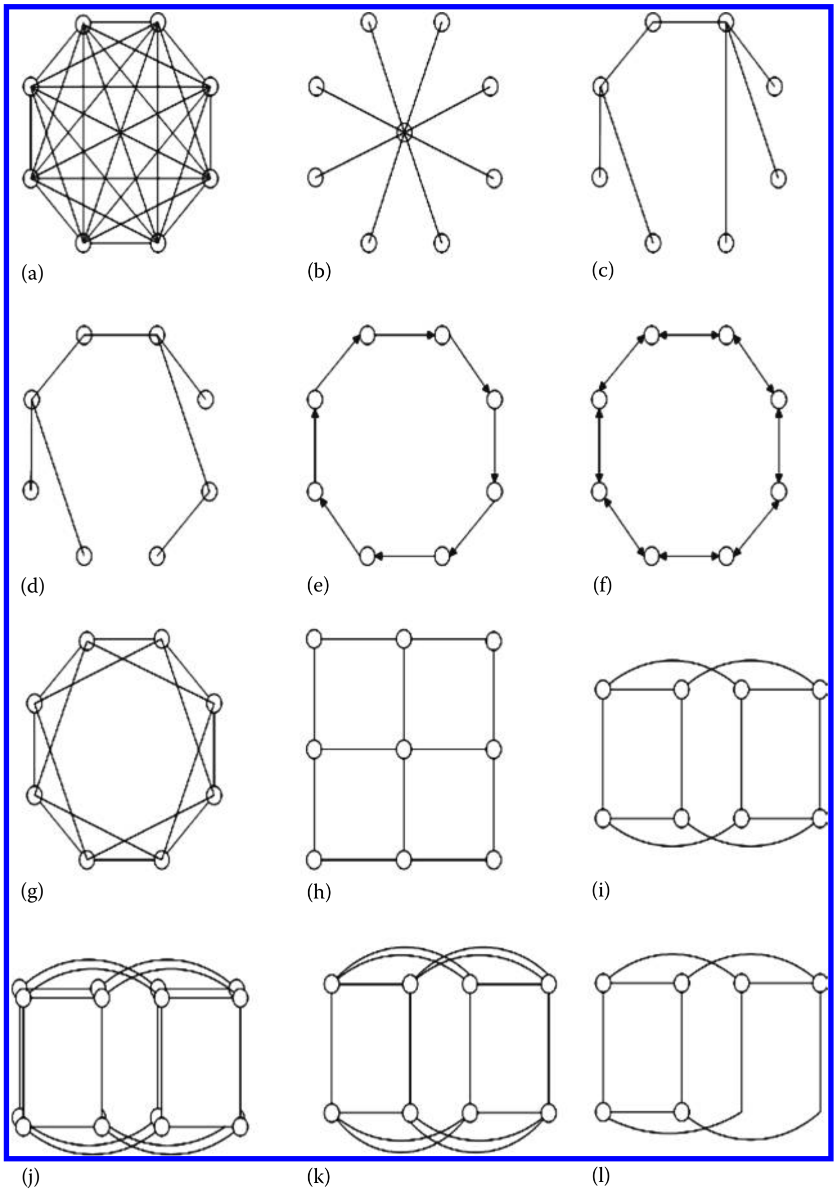

FIG. 33.9
Possible network topologies. (a) Completely connected, (b) a star, (c) a general tree, (d) a binary tree, (e) a unidirectional ring, (f) a bidirectional ring, (g) a multi ring, (h) a 2D mesh, (i) a hypercube, (j) a GFC, (k) an EHC, (l) a helical cube.

or more channels to which its transmitters and receivers are to be tuned. These assignments are fixed at any point of time and are known throughout the system. The network management can redo the assignments to improve the efficiency of the system. As a result, any connection between an arbitrary pair of nodes can be achieved by all nodes acting as intermediate routing nodes.

Current Optical Networks

Originally, as optical systems became popular, each telephone company started to have its own propriety optical system. However, in 1984 when AT&T was broken into many local companies who had to connect to various long-distance carriers, there was a need for standard protocol. Synchronous optical network (SONET) was proposed as the standard. Later, an international organization called Comite Consultatif International Telegraph et Telephonique identified a protocol called synchronous digital hierarchy (SDH) as the new protocol. Since then, virtually all of the long-distance carriers are using SONET-based communication on their optical lines in the United States and SDH in other places. Consequently, SONET/SDH has become the generalized standard protocol for optical communication and networking. Both systems work with high data rates of optical information on the fiber-optic lines. SONET and SDH are not identical and are different from each other in many aspects, but the general approach and idea are the same; consequently, they are often referred to as the SONET digital hierarchy. Table 33.1 shows the types of lines for SONET and SDH, as well as their speeds. The OC that stands for optical cable refers to SONET transmission characteristics, and the equivalent line name for SDH is STM.

Not all of the above systems have been popular. For example, OC-12 was perhaps one of the most popular systems while OC-9 did not become as widespread. The next generation of the OC-768 with 39.813 Gbps will have STM-256. Although both are basically the first generation and are designed for carrying voice traffic, they have been used for data as well. As the backbone of voice carrier channels, they have been used for carrying data since their early inception in 1985. Both SONET and SDH use single wavelength and EO conversion.

TABLE 33.1
SONET and SDH Equivalents and Line Speeds

SONET	Line Speed	SDH
OC-1	51.84 Mbps	N/A
OC-3	155.52 Mbps	STM-1
OC-9	466.56 Mbps	STM-3
OC-12	622.08 Mbps	STM-4
OC-18	933.12 Mbps	STM-6
OC-24	1.244 Gbps	STM-8
OC-36	1.866 Gbps	STM-13
OC-48	2.488 Gbps	STM-16
OC-96	4.977 Gbps	STM-32
OC-192	9.953 Gbps	STM-64

Next-Generation Optical Networks

Perhaps the most exciting part of next-generation optical networks is that it is originally a circuit switch network and the services are transparent. While transparency and the level of transparency is a debated issue, it is important for the reader to have a basic understanding of the concept of transparency.

In optical networks, transparency is a complicated issue. One can define the transparency based on the parameters of the physical layer (bandwidth, signal-to-noise ratio [SNR], etc.). It can also be the measurement of the signals remaining in the optical as opposed to interchanging between optical and electronic. Another issue is the type of signals the system can support. This includes the type of modulation formats and bit rates. In most of the available literature, the concept of an AON is defined as a network where the signal remains in the optical form throughout the network. This also includes the transparency to the modulation type. Transparent networks are attractive due to their flexible capabilities as well as higher data rate. A network is considered opaque if it requires its constituent nodes to be aware of the underlying packet format and bit-rate.

The lack of transparency is a pressing concern in current commercial networks. The need to handle data streams in the electrical domain with respect to the aforementioned factors engenders a large optical–electronic bandwidth mismatch. The bandwidth on a single wavelength is 10 Gbps today and is likely to increase to 100 Gbps in the near future. The enabling technologies for electronic processing of data at such high speeds are both costly and underdeveloped. Electronics will be hard-pressed to keep pace with the optical data rate as it continues spiraling upward.

An additional concern associated with the requirement of high-speed electronics is the prohibitive cost of infrastructure upgrades. For instance, if a legacy switch operating at 2.5 Gbps is present anywhere in the core network, all data passing through that switch is limited to data rate of 2.5 Gbps. Thus, any network upgrade requires the replacement of all legacy equipment, which is termed as a "forklift upgrade" in industry involving the massive overhaul of existing infrastructure. AONs avoid this problem in that data rate is only limited by the capabilities of the end stations. Thus, upgrading a connection does not require an upgrade in the core network and this enables metro operators to scale their networks to meet customer requirements and enhance their services.

OPTICAL FIBERS

The backbone that connects all of the nodes and systems together is optical fiber, which is a unique passive component.

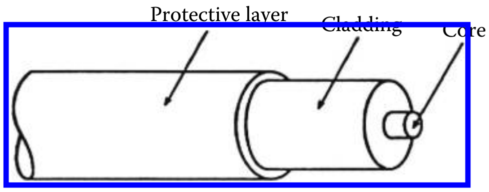

FIG. 33.10
Geometry of a step-index fiber.

It was in 1966 when K. C. Kao and G. A. Hockham of Standard Telephone Ltd. proposed this medium for long-distance communication [26]. They approached the problem by looking at the light attenuation of a signal and its energy in pure quartz glass and were the first group that found that, in principle, the attenuation could be as low as 20 dB/km. This was far less than other people thought or could demonstrate. Within a couple of years, engineers could manufacture fibers with 5 dB/km attenuation. Since then, the losses in the fiber have been reduced to 0.1–0.2 dB/km. The trend for better, more application-specific and versatile fibers is a continuous process.

An optical fiber consists of a cylindrical core made which is surrounded by a cladding whose refractive index is lower than that of the core as illustrated in Figure 33.10. According to ray theory or geometrical optics, light launched into the core of the fiber remains confined there due to total internal reflection, as shown in Figure 33.11. It can therefore be transmitted over long distances. Using the wave theory approach, an optical fiber can be modeled as a cylindrical waveguide that has guided modes above cutoff propagating through it. The number of modes supported by a fiber depends on the diameter of the core and the wavelength of the optical signal.

In general, there are two major types of optical fibers: multimode and single mode. Multimode fiber (MMF) comes in two varieties—stepped index and graded index. Figure 33.12 depicts the main operational concepts behind these fiber types.

MMF has a larger fiber core with a typical diameter of 30–100 μm. There can be a number of modes propagating in a MMF, and each mode has a different speed of propagation. Consequently, as the signals travel down the fiber, due to the speed variation the fiber causes the undesirable spreading of the signal. There are two remedies for this situation. The first remedy is achieved by creating the core material with a graded index and make multimode-graded index fiber. That will make the core act like a lens that will make the light rays focus toward the center of the core. The signal spreading is improved compared to the regular MMF called step-index fiber.

Attenuation and Loss

Attenuation or power loss is the reduction of the signal power as it travels along the fiber. Currently, fiber manufacturers have been able to achieve losses as low as 0.1–0.2 dB/km in optical fiber. It should be noted that the loss in dB/km is given by

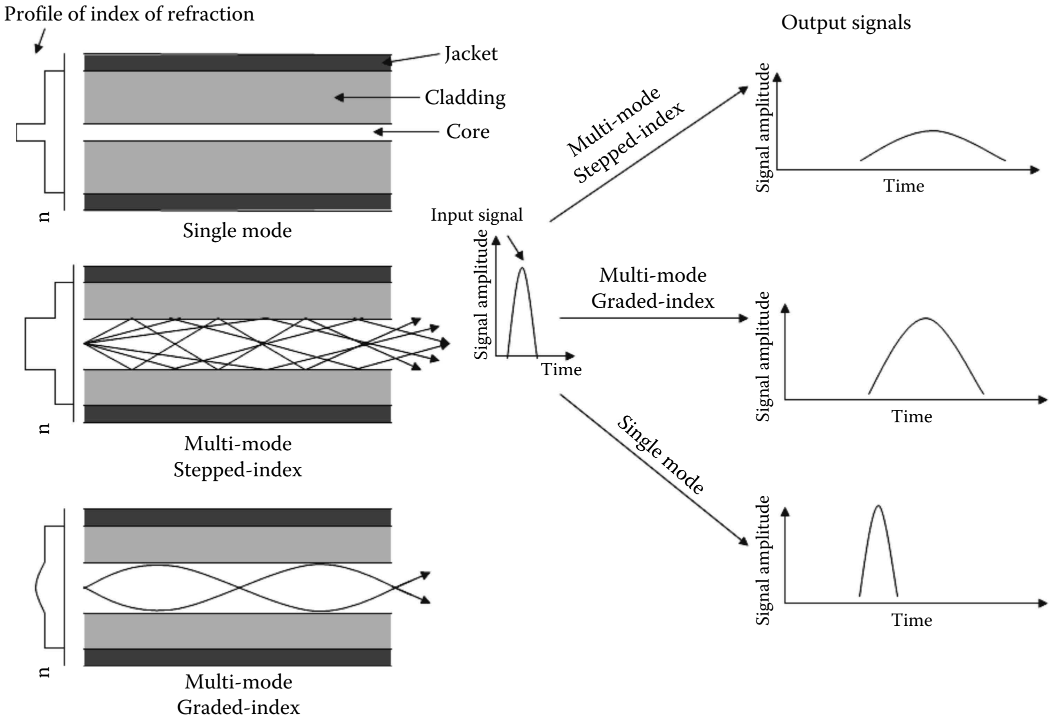

FIG. 33.11
Optical fiber types.

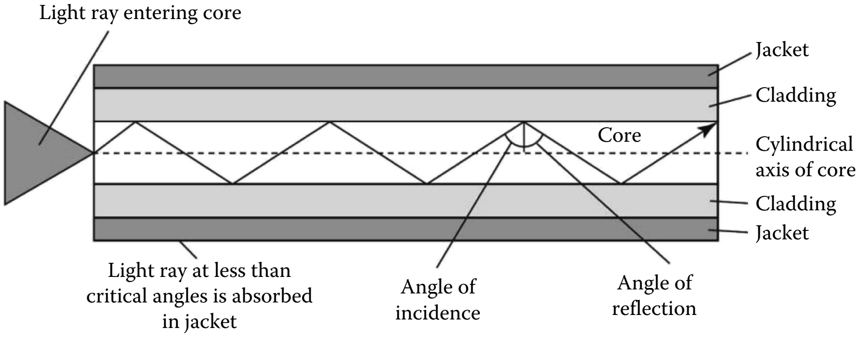

FIG. 33.12
Light propagation by total internal reflection in fibers.

$$\text{Attenuation} = 10\log_{10}\left(\frac{P_{out}}{P_{in}}\right) \quad \textbf{(33.1)}$$

The main cause of attenuation in fibers by intrinsic factors, such as material absorption and Rayleigh scattering, as well as extrinsic factors, mainly stresses introduced from the manufacturing process, environment, and physical bending [7]. Defects in the atomic structure of the fiber and impurities in its constituent material are the main reasons for absorption and scattering of optical energy. The associated losses are also wavelength dependent, decreasing dramatically with increasing wavelength. The absorption component of attenuation tends to be more dominant for wavelengths greater than 1 μm whereas Rayleigh scattering is the more dominant component at shorter wavelengths since it has a λ^{-4} dependence.

Another type of loss is bending loss which is radiative in nature. Though bending a fiber in a practical scenario cannot be avoided, the associated loss can be avoided by keeping the bend radius large (on the order of a few centimeters); the smaller the bend radius, the larger the loss as modes leak out more. Bending loss is also higher at longer wavelengths, for instance around the 1550 nm range as compared to that at 1330 nm.

Glass fibers have an attenuation minimum at 1552.5 nm, which is indeed highly desirable. However, their dispersion minimum is at 1320 nm. Manufacturers have made dispersion-shifted low-attenuation fibers that utilize nonlinear optical effects to shift the dispersion so that it occurs at the same wavelength as the attenuation at around 1550–1552 nm. In addition, recently there have been advances in fiber-optic design, and the new fibers are dispersion compensated. Also, new fibers by Corning have reduced the loss to between 1380 and 1480 nm, which will allow more room for DWDM (from 1280 to 1600 nm). It should be noted that with the recent developments in fiber, mid-band losses have been eliminated, opening up the entire range from 1280 to 1625 nm [37].

Dispersion

Dispersion is a measure of temporal spreading (broadening) that occurs when light is propagating through an optical fiber. As the signals broaden due to fiber dispersion, they can interfere with other signals. If there is enough overlap at the receiving end or at the output, the signals will become unrecognizable and there will be an undesirable loss of information. As such, dispersion is the primary factor that defines the maximum possible bandwidth limit of an optical network. Assuming a pulse has a temporal length of δt. As it spreads during propagation, it can be recognized if the spread is equal to or less than twice the original pulse. Consequently, we can give a conservative estimate of a transmission rate (in bps) of less than or equal to $2\delta t$.

Two general types of dispersion are chromatic dispersion (a linear effect) and polarization mode dispersion (PMD, a nonlinear effect). Chromatic dispersion occurs because light of different wavelengths at different speeds within a given medium. It can be broken down into material and waveguide dispersion components. Since a single wavelength light source does not exist, each light source has a central wavelength with a given bandwidth around a central wavelength. Each signal contains multiple components, each with different wavelengths and thus each component experiences a different effective index of refraction. They thus travel with different speeds down the fiber and this constitutes the material related component of chromatic dispersion. The second waveguide-related component arises from the different refractive indices of the core and cladding of optical fibers.

PMD arises due to the difference in propagation times of the different modes inside an optical fiber. In this case, the paths in the outer core travel a longer distance than the ones that travel in the inner core. Graded index fibers were introduced to force the modes to be focused at the center and consequently these fibers have less spreading and dispersion than their step-index counterparts.

Nonlinearities

Nonlinear effects in optical fibers are critical in the design of modern optical communications systems [1,2]. As mentioned earlier, contemporary optical networks employ WDM, with the industry moving to adopt DWDM systems. Consequently, optical power densities within fibers can be fairly high and unfortunately, nonlinear effects start becoming acute at these elevated power densities. Additionally, nonlinear effects accumulate with distance and cannot be compensated for, unlike linear effects such as attenuation and dispersion. The most integral nonlinear effects are stimulated Brillouin scattering (SBS), stimulated Raman scattering (SRS), self-phase modulation (SPM), cross-phase modulation (XPM), and four-wave mixing (FWM).

SBS occurs when the signal power reaches a level sufficient to generate small acoustic vibrations in the silica fiber. These vibrations alter the refractive index and scatter light. In turn, the scattered light generates acoustic waves that again lead to scattering. Thus, this phenomenon is called SBS. It can occur when only a single channel is transmitted. The result is that the light wave shifts slightly in wavelength from the original light wave wavelength.

SRS arises when signals with different wavelengths are transmitted simultaneously through a fiber, which is the case for WDM and DWDM systems. SRS transfers energy from shorter wavelength signals to those with longer wavelengths. This transfer occurs via the energy stored by the molecular lattice of the medium through which the signals propagate. In this case, one wavelength excites the molecular vibration and light of another wavelength stimulates the molecule to emit energy at that wavelength.

SPM is caused by the intensity dependence of the refractive index [52]. Thus, the energy at the peak of the pulse travels at a different velocity than that at the pulse edges. The associated disparity in the travel time for different sections of the same pulse adds up for long-distance transmission. An input optical pulse thus becomes spread out at the output and it is clearly seen that SPM limits the maximum bitrates in an optical communications system in the same manner as dispersion.

XPM occurs when light components of multiple wavelengths are traveling simultaneously through a fiber such as in WDM systems, the optical powers of individual signals can rapidly add up. Thus, the effects of SPM are enhanced, degrading the information carrying capacity of the system [36]. This can be alleviated by increasing the wavelength spacing between individual channels. For instance, XPM is negligible in standard SMF operating in the 1550 nm band with 100 GHz channel spacing. XPM becomes a significant problem at bitrates in excess of 10 Gbps in dispersion shifted fibers since light components of different wavelengths propagate with the same velocity.

Last but not least, WDM systems suffer from another nonlinearity known as FWM [23]. FWM arises from the nonlinear nature of the refractive index in optical fibers, which basically cause the generation of spurious frequencies that result in crosstalk and SNR degradation, thereby limiting the channel capacity of a WDM system.

LIGHT SOURCES

Optical sources for networks must have a sufficiently narrow linewidth, low noise, and sufficient optical power. Lasers and light-emitting diodes (LEDs) both meet these requirements. Laser is an acronym for light amplification by stimulated emission of radiation. These components convert high-speed input in electronic forms to optical signals. They consist of a heterojunction of two semiconductor materials with different direct-band-gap energies as illustrated in Figure 33.13. This heterojunction is known as the active or recombination region. The electronic input current is modulated in both lasers and LEDS, and they create light modulation in their

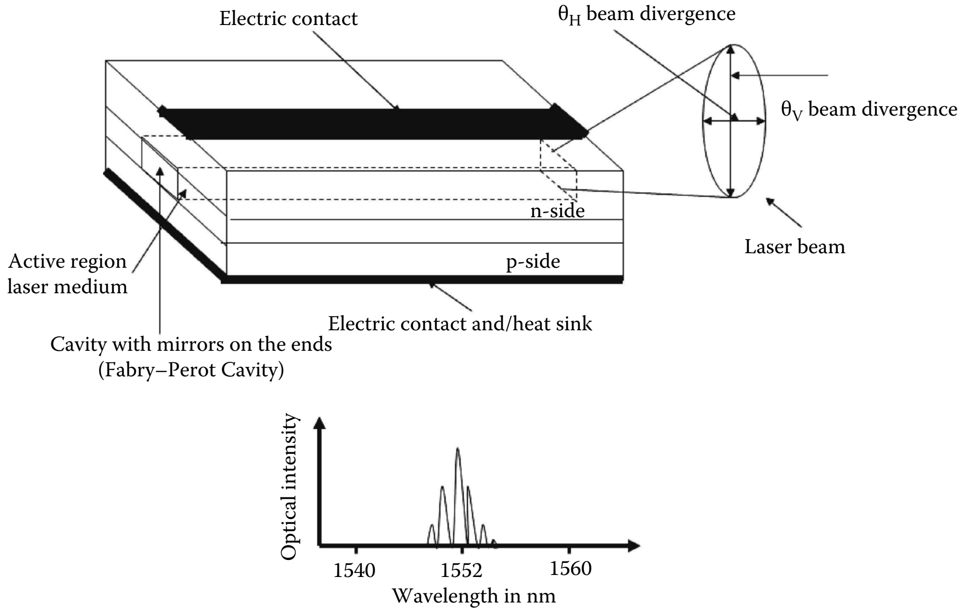

FIG. 33.13
Basic heterostructure laser and its output signals.

active region, which has the highest optical gain. In a laser, the active region is designed to have a feedback mechanism to make the light stimulate similar photons resulting in a spatial and temporal coherence of photon energies. This can be done by mirrors on both sides of the active region forming an optical resonant cavity. Due to their capability of generating such high gains, lasers are very sensitive to operating conditions. Slight fluctuations in the current, temperature, and general operating condition sometime cause Fabry–Perot (FP) lasers to jump between wavelengths and change their peak performance. However, with today's technology the operation can be very stable.

Traditionally, the lasers and LEDs in optical communication were single-frequency sources with their operating frequencies at 1310, 1480, and 1550 nm. The 1310 and 1480 nm are used for short-distance communication and the 1550 nm, which uses the low-loss and low-dispersion window of the dispersion-shifted optical fibers, is focused on long-haul communication. Today, the powerful 1480 nm lasers are mostly used for pumping fiber amplifiers.

The other suitable type of laser is the distributed feedback laser depicted in Figure 33.14. In this laser structure, a Bragg grating is utilized in the active region to enhance certain frequency selection. The sensitivity of the edge-emitting lasers that can cause them to jump between modes of operation due to slight fluctuation in the laser operation is much more controlled in this type.

A new class of lasers is the vertical cavity surface emitting lasers (VCSEL). VCSELs use advanced semiconductor fabrication techniques to create Bragg reflector-type mirrors that are parallel to the active region. They emit light from their top face and allow easier access for fiber coupling to the laser light [60]. The active area is small therefore they cannot emit more than a few mW of power. Thus, they are mostly used for local-area and data-communications applications.

The last group of lasers is power lasers. They are used in optical communication as pump lasers. Such lasers can amplify optical signals and provide very high output power up to 300–400 mW, or even sometimes higher if necessary. Historically, they appear in two groups: 980 and 1480 nm. The 1480 nm lasers show better stability and are easier to manufacture. However, the 980 nm lasers are more powerful and are the frontrunners as candidate for optical amplifier sources.

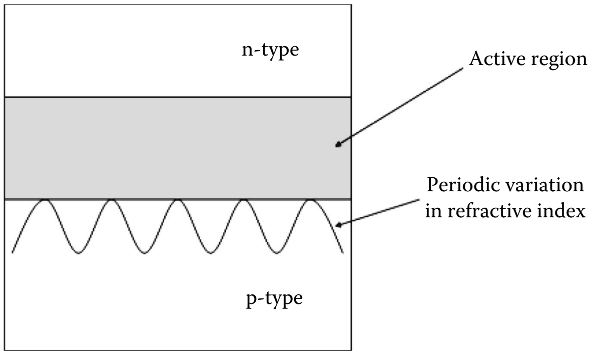

FIG. 33.14
Basic structure of a DFB laser.

OPTICAL RECEIVERS

Optical receivers are also known as light detectors and use two photodetection mechanisms: the internal and external photoelectric effects. In the external photoelectric effect, electrons are freed from the surface of a metal by the energy absorbed from an incident stream of photons. The vacuum photodiode and the photomultiplier tube are based on this effect. In the internal photoelectric effect exhibited in semiconductor junction devices, free charge carriers (electrons and holes) are generated by the absorption of incoming photons. This effect is utilized in avalanche photodiodes (APDs), pn-junction photodiodes as well as p-type, intrinsic, n-type (PIN) photodiodes [35,50]. These semiconductor junction diodes are most suitable for fiber systems as they are small, sensitive, and fast. In contrast to semiconductor light emitters that are forward biased, photodetectors are reverse biased. Their response time depends on the transit time or the time it takes for the free charges to traverse the depletion layer. PIN photodiodes, whose depletion region is just the width of the intrinsic layer, have a fast rise time (around 100 ps or less) and are therefore suitable for high-speed data networks. APDs have a higher sensitivity and speed comparable to the PIN photodetector and are therefore used in loss-limited systems such as long-distance links. In other systems, PIN types are preferred as they are less expensive, have lower temperature sensitivity, and require lower reverse bias voltage than the APDs.

OPTICAL SWITCHES

Transmission components alone do not constitute an optical network. A variety of processing needs to be performed on the optical signals within the network, including multiplexing, demultiplexing, grooming, and switching. Optical switches can be broadly classified as either opaque or transparent depending on their implementation technologies. Opaque switches, also billed as optical cross-connects, convert the incoming optical signals into electrical form. The actual switching is then performed electronically using an electronic switching fabric with the resultant signals converted back to optical form at the output. This conversion to the electrical domain presents several advantages including regeneration of the optical signal, free wavelength translation, as well as straightforward performance and fault management.

Transparent switches, also billed as photonic cross-connects, do not perform any OEO conversions. This allows them to function independent of the optical data type, format (e.g., SONET, GbE, SCM) or rate, albeit only over a range of wavelengths termed the passband. Researchers have been exploring different ways of supplanting the electronic switch fabrics present in current commercial optical networks. Successful optical switching technologies should ideally demonstrate superiority in power consumption, scalability, insertion loss (IL), polarization-dependent loss, wavelength dependency, switching speed, and crosstalk. The technologies discussed below have individual niche areas and it is highly likely that they will co-exist on networks as each type represents different engineering trade-offs. The main contemporary switch technologies are microelectromechanical (MEM), acousto-optical (AO), electro-optical (EO), thermal–optical (TO), and magneto-optical (MO).

Microelectromechanical Systems

MEMS switches are either free space (membranes, micromirrors) or based on planar moving waveguides that redirect light beams to the desired output port [18,22,25,32,44,47,57]. An example 2D MEMs switch is shown in Figure 33.15. They also vary in the actuation mechanism used; electrostatic vs. magnetostatic, latching vs. non-latching. Free space variants suffer from higher ILs due to beam divergence (~3 dB), slower switching times (ms), high actuation voltage/current requirements and higher power dissipation for non-latching configurations (~80 mW). Waveguide variants offer faster switching times (100 ns) and lower ILs (~1 dB) at the cost of higher crosstalk (about −30 dB).

Acousto-Optic

AO switches are based on ultrasonic waves traveling within a crystal or planar waveguide that deflect light from one path to another [4,6,29,43] as illustrated in Figure 33.16. When a mechanical vibration is present in a material it causes regular zones of compression and tension within the material. In most materials, this causes changes in the refractive index. This periodic pattern of refractive index changes forms a diffraction grating that causes the incoming light to be diffracted. Control of the ultrasonic wave amplitude and frequency enables control of the amount and wavelength of light that is diffracted. AO switches are able to handle high power levels and offer reasonable IL (~3 dB) and switch times (~40 µs) but suffer from poor isolation (~−20 dB) and power efficiency as well as inherent wavelength dependency.

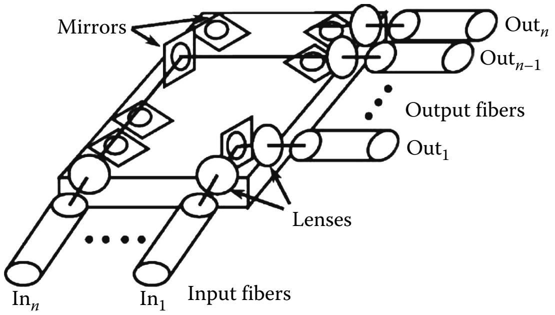

FIG. 33.15
Example crossbar 2D MEMs switch.

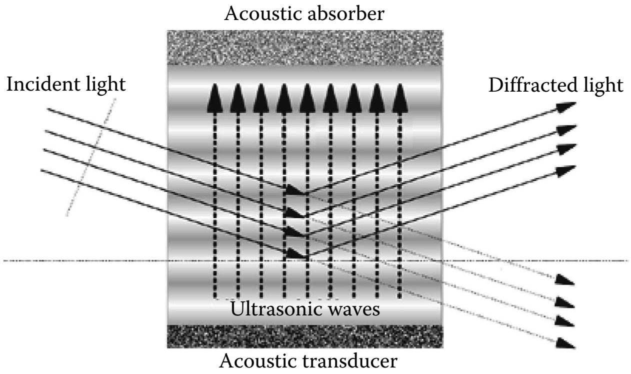

FIG. 33.16
Creation of diffraction grating by ultrasonic waves.

Electro-Optic

EO switches are among the most mature available and have been implemented using semiconductor optical amplifiers (SOAs), $LiNbO_3$, liquid crystal, electroholography, and switchable waveguide Bragg gratings [9,16,30,48,59]. An EO modulator using a $LiNbO_3$ crystal to impart a change in the refractive index of the material that varies linearly with field strength is shown in Figure 33.17. Depending on the variant, they offer ILs ranging from <1 to 10 dB, switch times from 10 ns to 1 ms and isolations of −10 to −40 dB. However, the majority of them have a strong wavelength dependency and those that do not are typically subject to higher ILs. SOA-based switches also potentially suffer from a limited dynamic range.

Thermo-Optic

TO switches are based on either the thermal behavior of materials or the waveguide TO effect [17,28,54,56,61]. Interferometric TO switches heat the material in one of the interferometer legs to generate a phase shift relative to the other leg, leading to interference effects between the two light beams when they are recombined. Digital TO switches generally utilize the interaction of two silica waveguides on silicon as shown in Figure 33.18. Heating the material changes the refractive index of the waveguide, imparting a phase difference and thereby altering the selectivity of the output ports. They typically consume more power due to the heating process (~70 mW) and have a slow switch time (~10 ms).

Magneto-Optic

MO switches are based on the Faraday rotation of polarized light when it passes through a MO material in the direction

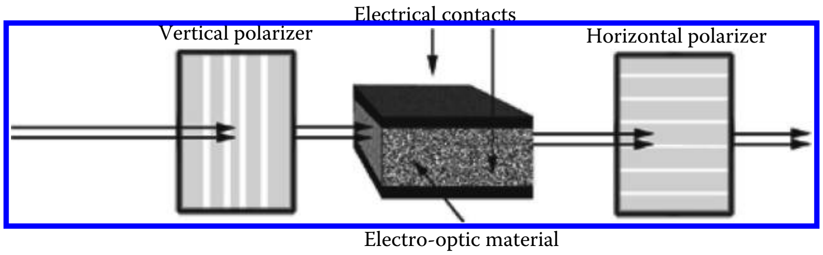

FIG. 33.17
EO modulator using $LiNbO_3$ crystal.

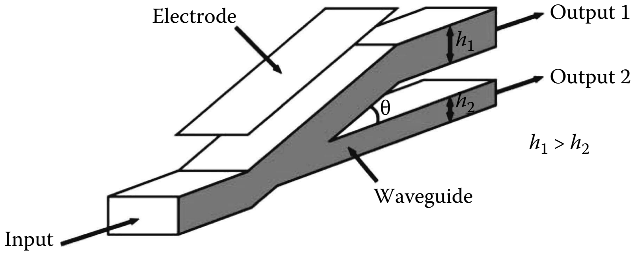

FIG. 33.18
Digital thermo-optic waveguide switch.

of an applied field [53]. Polarization is a property ascribed to electromagnetic waves that describes the orientation of their field vectors. As a 3D object, an electromagnetic wave can be considered to be a superposition of its two orthogonal components orientated in a plane perpendicular to the propagation direction [45]. Pragmatically speaking, changing the polarization of an electromagnetic wave is an indirect method of controlling the relative phase of its constituent orthogonal components. One method of achieving this is via the exploitation of the Faraday Effect in a MO material. Faraday rotation arises from the phase difference develops between the right and left circularly polarized components of linearly polarized light that is transmitted through the MO material. This manifests itself as a rotation of the linear polarization by the Faraday rotation angle θ_F with the overall process illustrated in Figure 33.19. MO switches use an interferometer to convert the phase modulation achieved via the Faraday Effect to an amplitude modulation as shown in Figures 33.20 and 33.21. There has not been as much work done investigating these types of switches due to the lack of sufficiently high-quality MO materials. Recent advances in bismuth-substituted iron garnets and orthoferrites [20] have yielded materials with a high MO figure of merit, giving low ILs, ultrawide bandwidths, and a higher degree of rotation for less applied field.

Several comprehensive reviews of optical switching technologies and commercially available devices are given in the references [24,33,42].

MULTIPLEXERS/DEMULTIPLEXERS

Multiplexers (MUX) and demultiplexers (DEMUX) are used to combine or separate, respectively, multiple wavelengths in a single channel in a WDM system. Numerous methods of filtering and adding are utilized in MUX and DEMUX technology. The components used in MUX/DEMUX are also used for wavelength filtering and wavelength routing.

The most popularly used filter in the WDM (and DWDM) optical communication are thin-film filters, which are fairly straightforward to manufacture. While thin-film technology is mature, the devices are complex with very fine component requirements. They allow a few hundred GHz channel spacing in the WDM systems. The filter is based on the interference effect created by thin-film coatings on glass substrates and is illustrated in Figure 33.22.

Another type of filter is based on FBGs. This in essence allows a selective Bragg grating inside a single fiber. Figure 33.23 depicts the general concept. It is possible to design Bragg reflectors with narrow pass-through filter capabilities. This filter is designed by putting gratings along the lengths of a single-mode fiber. A Bragg reflector can be achieved by alternating thin layers of materials that alternatively change the index of refraction from high to low. In general, one can design a filter that only allows a single band of wavelengths through and the rest are reflected back.

The next type of component is the arrayed waveguide grating that one can think of as a series of waveguides, fiber strings, or light paths in a specially designed Si or GaAs [49]. The input signal (with various wavelengths) enters an array of waveguides. Each waveguide is unique in length. The

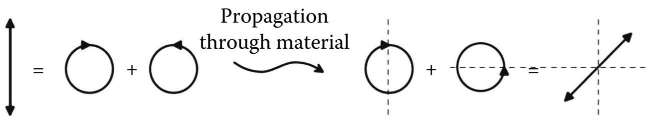

FIG. 33.19
Illustration of the Faraday rotation mechanism.

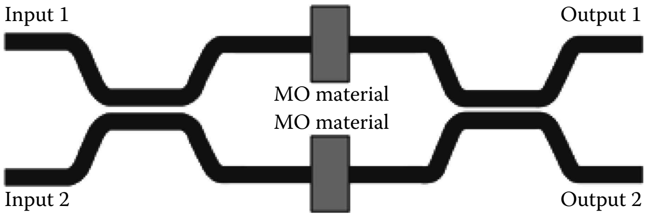

FIG. 33.20
MO switch based on the Mach–Zehnder interferometer configuration.

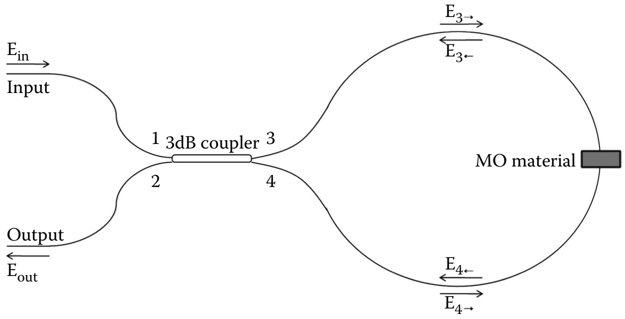

FIG. 33.21
O switch based on the Sagnac interferometer configuration.

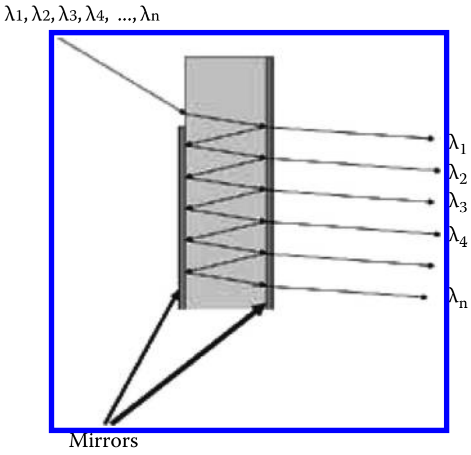

FIG. 33.22
Thin-film filter.

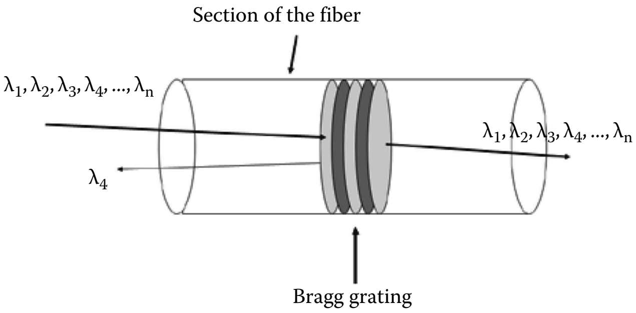
Section of the fiber
$\lambda_1, \lambda_2, \lambda_3, \lambda_4, ..., \lambda_n$
λ_4
$\lambda_1, \lambda_2, \lambda_3, \lambda_4, ..., \lambda_n$
Bragg grating

FIG. 33.23
FBG optical filter.

slight delay difference in each guide causes the light to go through different phase shifts. Consequently, this results in a different diffraction pattern for each wavelength that allows wavelength separation at the end of the array. Figure 33.24 illustrates an arrayed waveguide filter.

Interferometers are of various types such as Mach–Zehnder, Michelson and Sagnac interferometers. Mach–Zehnder interferometers (MZIs) has been used successfully as both filters and DEMUXs. MZIs can be used to separate signals in the 1.3 and 1.55 µm bands. A 2×2 MZI is constructed using two 3 dB couplers as shown in Figure 33.25. A phase difference is created by the path difference ΔL between the two arms. If the phase difference is an odd integral multiple of π, the wavelengths passes to the bar port. On the other hand, if it is an even multiple of π, the wavelengths passes to the cross port. The interferometer can be tuned, for example, heating one arm of the MZI results in a change in the refractive index that in turn affects the phase relationship between the two arms.

An optical add drop MUX/DEMUX is used in a WDM system to drop a specific wavelength at a certain point in the link and add a signal to the link as illustrated in Figure 33.26. The physical implementation is achieved by the use of filters and optical circulators shown in Figure 33.27. A MZI using two FBGs can also be used, also shown in this figure.

AMPLIFIERS

These systems amplify the signal in the optical domain and are deployed to strengthen an attenuated optical signal before it becomes too weak to be detected. Erbium-doped

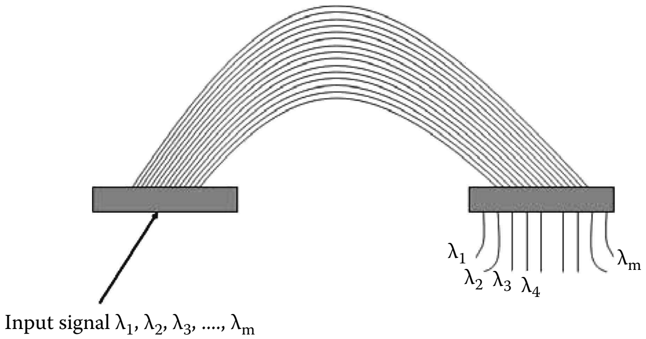
λ_1
λ_2 λ_3 λ_4
λ_m
Input signal $\lambda_1, \lambda_2, \lambda_3, ..., \lambda_m$

FIG. 33.24
AWG optical filter.

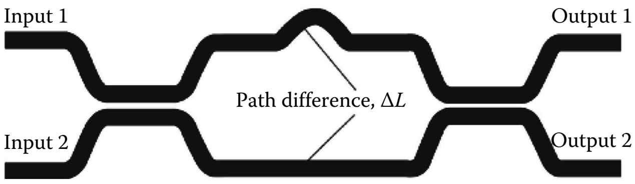

FIG. 33.25
Mach–Zehnder interferometer.

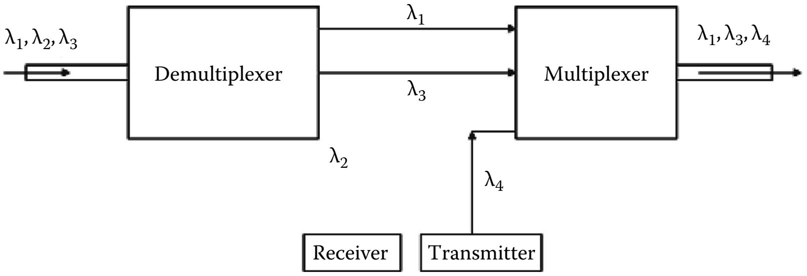

FIG. 33.26
Optical add/drop system.

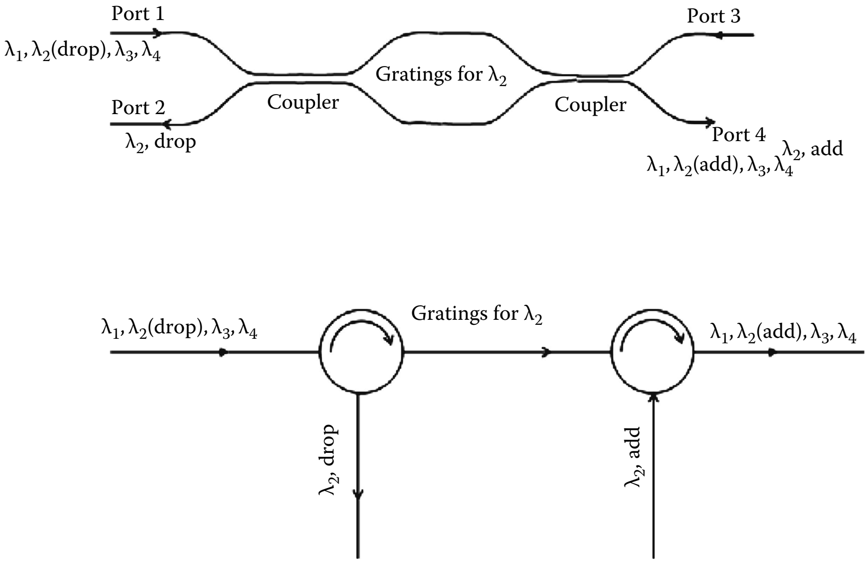
Port 1
λ_1, λ_2(drop)$, \lambda_3, \lambda_4$
Port 2
λ_2, drop
Coupler
Gratings for λ_2
Coupler
Port 3
Port 4
λ_2, add
λ_1, λ_2(add)$, \lambda_3, \lambda_4$
λ_1, λ_2(drop)$, \lambda_3, \lambda_4$
Gratings for λ_2
λ_1, λ_2(add)$, \lambda_3, \lambda_4$
λ_2, drop
λ_2, add

FIG. 33.27
OADM in an interferometric configuration with gratings (top) and circulators with gratings (bottom).

fiber amplifiers (EDFAs), Raman amplifiers, and SOAs are the three different types of amplifiers considered here.

Erbium-Doped Fiber Amplifiers

An EDFA consists of a specially designed fiber whose core is doped with Er^{3+} ions [11]. The Er^{3+} ions are energized via a pump laser typically at a wavelength of 980 or 1480 nm. All doped fiber amplifiers amplify light incident through stimulated emission therefore, an optical amplifier can be considered as a laser without feedback. EDFAs are recently becoming one of the most important amplifications in optical network systems. Recently, their design has become much more sophisticated than before. In newly designed EDFA systems, one finds elements that take care of dispersion compensation, variable optical attenuators, gain equalization, pumping sources (both 980 and 1480 nm in most of the new ones), and specially doped fiber.

Raman Amplifiers

While EDFAs provide a large boost in a short distance, the Raman amplifier provides a small boost in a large distance [40]. The Raman amplifier uses the non linear optical effect called SRS, which is defined as nonlinear scattering involving optical phonons. The idea is utilizing the energy from the pump source, transferring it to the atomic structure of the fiber, and retransmitting it to the incoming wave. This process causes a frequency and wavelength shift. In general, there is a predictable 100 nm wavelength shift in this effect. The effect takes place over a distance of 10 km inside the fiber. Several pump lasers in about 1480 nm pump the amplifier and energize the fiber.

Semiconductor Optical Amplifiers

Generally speaking, there are two types of SOAs: resonant FPA and non-resonant traveling wave amplifiers [39]. In an FPA the ends of the semiconductor crystal are cleaved at an angle such that they are partially reflective and form a FP cavity. A reflective coating at the ends may also be used to enhance the reflectivity. An input signal gets amplified as it reflects back and forth in the cavity until it is emitted at a higher intensity.

The SOAs exhibit severe crosstalk due to saturation effects. For two signals propagating simultaneously through an SOA, the signal with a high enough power saturates the SOA or depletes the population inversion thus the low power signal experiences no gain (the signal may even be absorbed). The spontaneous emission lifetime of SOAs is in the order of nanoseconds therefore the crosstalk is severe even for bitrates of Gbps. On the other hand, the spontaneous emission lifetime of an EDFA is about 10 ms; therefore, crosstalk is only significant for bit rates less than a few kHz. Thus, EDFAs are more popular than SOAs for the purpose of amplification in WDM systems.

PASSIVE COMPONENTS

Power Splitters/Couplers

Power splitters and couplers are passive components that split the power of an input signal at the output or combine input light sources onto the same signal paths, respectively. These can be directional or bidirectional and are always used in the optical fiber system when one needs to tap into the fiber for testing. These components can be fabricated either from optical fibers or by means of planar optical waveguides. Fiber couplers are made by fusing two fiber cores together in the middle as shown in Figure 33.28. Optical waveguide couplers [2] are made by using materials such as GaAs, InP, SiO2, LiNbO3, etc. The coupling ratio depends on the length of the coupling section. The couplers can also be used to separate wavelengths when they are combined with filters. Wavelength-dependent couplers can be used for wavelength-selective devices.

When two waveguides are placed in proximity to each other, modes couple from one waveguide to another; a quantitative analysis of this phenomenon called coupled mode theory can be found in Ref. [58]. In a fiber coupler, the cores are fused together and elongated, a process that decreases the core diameter of the fibers. This allows a greater portion of an optical mode to propagate in the cladding, where this mode will couple to the core of the other fiber. In the coupling region, the cladding is removed and optical mode from one core couples to another. At the end of the coupling region, the cores increase in diameter and the modes are confined within the cores to get separated power in the output fibers. The output fields (E_{out1}, E_{out2}) for a 2×2 directional coupler can be expressed in terms of its input fields (E_{in1}, E_{in2}) as

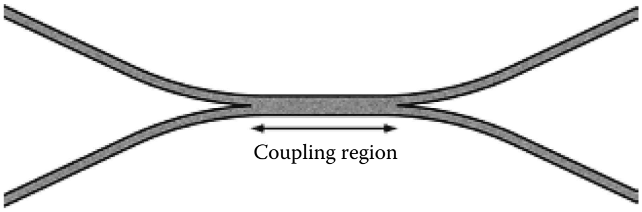

FIG. 33.28
Fused fiber coupler.

$$\begin{pmatrix} E_{out1} \\ E_{out2} \end{pmatrix} = e^{-j\beta L} \begin{pmatrix} \cos(\alpha L) & j\sin(\alpha L) \\ j\sin(\alpha L) & \cos(\alpha L) \end{pmatrix} \begin{pmatrix} E_{in1} \\ E_{in2} \end{pmatrix} \quad \textbf{(33.2)}$$

where
L is the length of the coupling section
α is the coupling coefficient

The value of α depends on the width of the waveguides in the coupling region, refractive index of the waveguiding region and substrate as well as the proximity of the waveguides. The most ubiquitous couplers are those with a 50:50 coupling ratio (3 dB couplers). However, any ratio from 1:99 to 50:50 is possible. The power-transfer function of a directional coupler with one input can be written as

$$\begin{pmatrix} P_{out1} \\ P_{out2} \end{pmatrix} = \begin{pmatrix} \cos^2(\alpha L) \\ \sin^2(\alpha L) \end{pmatrix} P_{in1} \quad \textbf{(33.3)}$$

For a 3 dB coupler $\alpha L = (2n + 1)\pi/4$, where n is a positive integer and αL can be adjusted in order to obtain the desired splitting ratio. It is also important to note that for a 3 dB splitter, the electric fields at the two outputs have the same magnitude but have a phase shift of $\pi/2$.

Isolators/Circulators

Isolators prevent the strong laser light from reflecting back onto the other components. It is important to isolate transmitters such as lasers and optical amplifiers from back scattering and reflection of light as such effects can cause noise and degrades the performance of the devices. Thus, the IL of an isolator for a backward traveling signal (i.e., isolation) should be high while the IL for the forward traveling waves should be low. Typical values are 1 and 40–50 dB for IL and isolation, respectively. The most popular isolators utilize Faraday rotation to ensure one-way propagation and no back reflection. These are therefore important optical components used for maintaining healthy optical links and for protecting other expensive optical components.

Circulators are non-reciprocal devices that allow a light signal to travel from one port to another sequentially only in one direction. Circulators create multiple ports for routing signals and traffic as well as for adding or dropping certain signals (wavelengths) in the signal collection.

The state of polarization (SOP) of light propagating in a fiber refers to the orientation of its electric field vector on a plane that is orthogonal to its direction of propagation. A polarizer allows light energy with SOP oriented parallel to its axis while it completely blocks light with SOP orthogonal to its axis. Polarizers can be realized using crystals called dichroics, which have the property of selectively absorbing light with one SOP. A simple isolator is shown in Figure 33.29. The first polarizer that the signal encounters polarizes the input in the vertical direction. A Faraday rotator that rotates

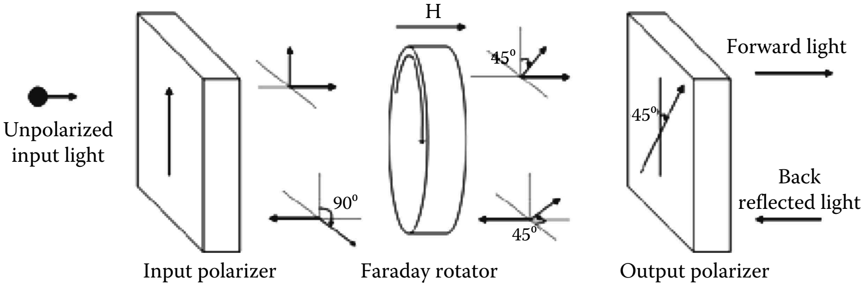

FIG. 33.29
Operational principle of an isolator.

the SOP, say, clockwise by 45° is placed after the polarizer as shown. Another polarizer that passes only SOPs with this 45° rotation is placed after the Faraday rotator. The input signal thus passes unblocked thorough the whole assembly. Now the reflected light with the same 45° SOP as the output polarizer passes through the output polarizer and is rotated 45° in the same direction by the Faraday rotator. Its polarization is therefore orthogonal to that of the input polarizer and is thus blocked from reaching the input side.

A polarization independent isolator is more practical to use in optical networks. This type of isolator can be made by separating the random SOP into orthogonal components and treating them separately. Here, a polarization beam splitter splits the incoming SOP into vertical and horizontal polarizations; a Faraday rotator rotates each SOP by 45°, say, in the clockwise direction. This is followed by a half-wave plate, which is a reciprocal device that means waves from left to right are rotated 45° clockwise and waves from right to left are rotated 45° counterclockwise. The signals are combined by a beam combiner at the output. For reflected light, the half-wave plate and the Faraday rotator cancel the change in the SOP, resulting in signals that are not combined at the input side.

OTHER SYSTEMS

Regeneration

Optical signals in long-haul communication have to travel hundreds of kilometers to reach their destinations. The signals distort mainly due to fiber dispersion, crosstalk, splice loss, and fiber absorption; therefore, the destination/intermediate node must have the ability to regenerate the optical signal. Degradation of the signal is, therefore, in two domains—time and space. An in-line optical regeneration scheme in an interfacing node between the long link and the destination nodes is a solution. Regeneration is of three types: 1R (re-amplification), 2R (re-amplification and re-shaping), and 3R (re-amplification, re-shaping, and re-timing).

A repeater, also called a transceiver, is a combination of a transmitter and a receiver, as shown in Figure 33.30. A repeater module first receives the weakened signal from the incoming cable. The receiver transfers the information in the electronic domain. A decision about whether the bit is 0 or 1 is made, and a new electrical pulse is generated. Finally, the cleaner version of the signal is sent to the transmitter part as an electronic signal and is transmitted as an optical signal. However, repeaters do not work for fiber-optic networks, as the associated electronics depend upon the bit rate and the data format, which may vary widely in a fiber network.

Optical 3R regenerators are expected to replace electrical regenerators because they can directly process optical signals in the optical domain without conversion to an electrical signal, which eliminates the need for many electrical circuits. Various types of optical reshaping and retransmitting (2R or 3R) regeneration operations have been proposed and intensively investigated [10,31,41,46], the goal being cost reduction as well as high-speed operation and network applications. A regeneration operation using MZIs integrated with SOAs is particularly attractive because of very high speed and low switching energy operation, as well as possible integrated configuration with other devices. Although some of them used to show very large polarization-dependent loss of several decibels, polarization-insensitive operation is becoming possible because the fabricating technique is mature. Saturable absorbers [41] have also been demonstrated as all optical regenerators.

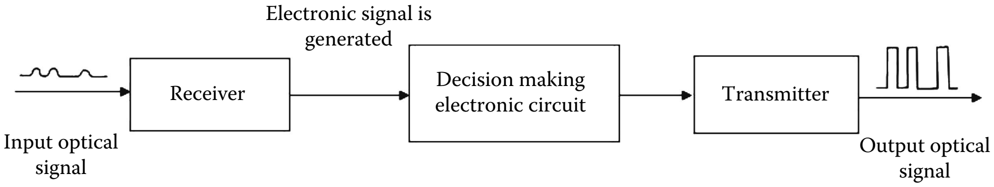
Electronic signal is generated
Receiver
Decision making electronic circuit
Transmitter
Input optical signal
Output optical signal

FIG. 33.30
3R repeater.

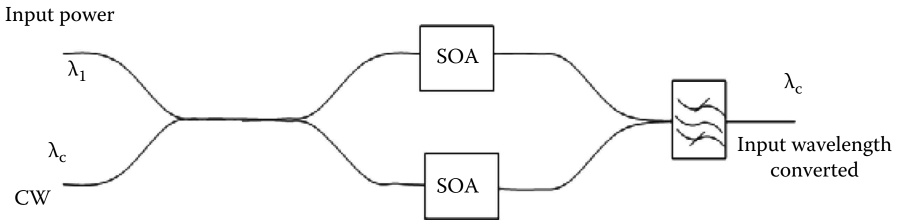

FIG. 33.31
Optical add/drop system.

Wavelength Conversion

As a network's size grows and more users are added, efficiency becomes a pressing concern. It is possible in a multichannel DWDM system to have only one of the channels fully utilized. In such a case, a new user trying to access the network resources may be rejected. However, it may be possible for the user to utilize the network resources by shifting to another channel. To achieve this, the user's signal needs to be shifted to a new channel. This is done by a wavelength converter. Wavelength converters are devices that receive the incoming signal and change it to a signal of the same information but on a different wavelength to allow it to be sent over another channel that has the available capacity.

Wavelength conversion is typically done with SOAs [3], and non linear effects such as cross-gain modulation (XGM) [14], XPM [51] as well as FWM [12] are utilized for wavelength conversion. When using XGM the modulated signal at wavelength λ_1 is input to the SOA along with a low-power CW signal at wavelength λ_2, which is the desired wavelength. For bit λ_1, the gain of the SOA is saturated and λ_2 does not get amplified; however, for bit 0 λ_2, the gain is amplified. In this way, the bit pattern of the input signal is transferred to the signal at the desired wavelength λ_2; the bit pattern is, however, interchanged. The use of an absorbing medium, for example, an electro-absorption modulator, in place of an SOA solved this bit reversal problem [15]. It works on the principle of cross-absorption saturation.

Wavelength conversion is also implemented by using the MZI configuration in which an SOA is inserted in each arm of an MZI [13] as shown in Figure 33.31. For bit 1, the SOA through which λ_1 passes is saturated and the refractive index in that arm is increased. The interferometer can be made such that λ_c is passed to the output for bit 1 and is blocked for bit 0, thus the bit pattern is transferred to the desired wavelength. In the MZI scheme, the bit pattern is not reversed and the ON–OFF contrast ratio is high as nothing is output for bit 0.

In the FWM scheme, an intense CW pump beam is launched into the SOA along with the signal whose wavelength needs to be converted. If λ_1 and λ_2 are the wavelengths of the original signal and the converted signal, respectively, then the pump signal wavelength should be $(\lambda_1 + \lambda_2)/2$. Then a replica of the input signal is obtained at λ_2 carrier wavelength. This technique can work at bit rates as high as 100 Gbps as the time scale for the physical process involved, that is, the intraband relaxation process is about 0.1 ps [2].

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